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Dynamics of an M-Level Atom Interacting with Gravity Fields. I. Effects of the Level Number on Quantum Collapse and Revival

by

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Dynamics of an M-Level Atom Interacting with Cavity Fields.
I. Effects of the Level Number on Quantum Collapse and Revival

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Abstract

A quantum mechanical theory is developed to treat the interaction of a multilevel atom with cavity fields of arbitrary detunings. The Hilbert space spanned by the energy eigenvectors is divided into subspaces specified by eigenvalues of the total excitation number, which is a constant of motion. Since the total Hamiltonian does not connect states in different subspaces, it can be diagonalized in each subspace independently. The time evolutions of the level occupation probabilities and the mean photon number are investigated numerically, and their variations with the atomic level number and the initial photon number are discussed. Their relation with the field squeezing is also discussed.

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I. Introduction

The simplest theory that describes quantum mechanically the interaction of light with matter is the Jaynes-Cummings (JC) model[1] in which a two-level atom interacts at resonance with a single mode of cavity field initially in the coherent state. The model has been investigated extensively, and a number of interesting phenomena have been found. In particular, the discovery of quantum collapse and revival[2] has prompted further studies of more general cases. A three-level atom interacting with two-mode cavity fielas initially in different states has been studied[3-6] for the quantum collapse and revival of the mean photon number as well as the atomic occupation probabilities.

More recently, the problem has been extended to the nonresonant interaction case[7-9] in which the cavity fields can have arbitrary detunings. The dependence on detuning parameters of the time evolution of atomic occupation probabilities, photon number distributions and fluctuations, and field coherence properties have been examined in great detail, and many novel phenomena have been discovered. For instance, the intitially coherent stimulated field does not lose its coherence as a result of interaction with the atom when the interaction is far away from resonance. Hence, the idea[10] that the atom serves as a nonlinear filter to screen out the coherence of the field is no longer true in general.

The development of frequency-tunable lasers has made it possible to study one atom in a cavity,[11] and hence the predictions of the ideal JC model can be tested experimentally. As a matter of fact, the quantum phenomenon of collapse and revival has recently been observed in a superconducting cavity.[12] The Rydberg atoms used in the experiment are excited in steps by the tunable laser to a state with the principal quantum number n as large as 30. It is well known that the rate of change dn/dE of the atomic level density is

proportional to n^3, so that dn/dE can be very large in this region of n. We believe that there exist degenerate multiphoton transitions in addition to the single-photon transition in this region of high-density energy levels. In fact, a degenerate two-photon transition has already been observed experimentally.[13] It is therefore desirable to investigate the dynamical behavior of the atom in such degenerate multiphoton processes.

In this series of papers, we attempt to study the system of an M-level atom interacting with cavity fields of arbitrary detunings. A fully quantum mechanical theory is developed, and the mean photon number and atomic level occupation probabilities are calculated for various initial photon number $\bar{n}$ and level number M. The time evolution of these probabilities and the mean photon number in the multiphoton processes and their relations to the squeezing are discussed. The squeezing and antibunching of the field and effects of level number on photon statistics will be investigated separately and published elsewhere.[14,15]

II. General Formalism

Consider a single atom interacting with the radiation field in a cavity. The atom has M nondegenerate energy levels as shown in Fig. 1. The level separations may be arbitrary. When the atom is in the state i, its state vector is $|i\rangle$ and energy is $\hbar\omega_i$. It interacts with the cavity field of frequency Ω when it makes transition. For simplicity, we restrict our attention to processes involving only one-photon dipole transitions between adjacent atomic levels.

The total Hamiltonian of the atom-field system is, in the rotating wave approximation,

$$H = \sum_{i=1}^{M} \hbar\omega_i A_i^\dagger A_i + \hbar\Omega a^\dagger a + \hbar\left(\sum_{i=1}^{M} \lambda_i A_{i+1}^\dagger A_i a + \text{h.c.} \right) , \qquad (1)$$

where λ_i are the atom-field coupling constants. The operator $a^\dagger$ creates a photon, and $A_i^\dagger$ creates an atom in the state i. While $a^\dagger$ and a obey the usual commutation relation, $A_i^\dagger$ and A_j satisfy the anticommutation relation

$$[A_i, A_j^\dagger]_+ = A_i A_j^\dagger + A_j^\dagger A_i = \delta_{ij} \quad . \qquad (2)$$

We now define the operator

$$E_{ij} = A_i^\dagger A_j \quad , \quad i,j = 1,2,3,\ldots,M \qquad (3)$$

which satisfies the commutation relation

$$[E_{ij}, E_{\mu\nu}] = E_{ij}E_{\mu\nu} - E_{\mu\nu}E_{ij} = \delta_{\mu j}E_{i\nu} - \delta_{i\nu}E_{\mu j} \quad . \qquad (4)$$

This is a U(M) Lie algebra relation. The first-rank and second-rank Casimir operators of a U(M) Lie algebra are, respectively,

$$C_1 = \sum_{i=1}^{M} E_{ii} = \sum_{i=1}^{M} A_i^\dagger A_i \qquad (5a)$$

$$C_2 = \sum_{i=1}^{M} \sum_{\mu=1}^{M} E_{i\mu}E_{\mu i} = (M+1-C_1)C_1 \quad . \qquad (5b)$$

Since the Hamiltonian H is composed of the photon operators and U(M) Lie algebra operators, it must commute with C_1 and C_2, which can easily be verified by direct calculation.

Let $|i\rangle$ be the atomic state vector for the atom in its i-th level. It can be readily shown that all M such states are simultaneous eigenstates of both the operators C_1 and C_2 with the same eigenvalues. That is, for $1 \leq i \leq M$,

$$C_1|i\rangle = |i\rangle \tag{6a}$$

$$C_2|i\rangle = M|i\rangle \quad . \tag{6b}$$

The conservation of C_1 means the conservation of the number of atoms during the interaction process, and the conservation of C_2 simply means that the number of atomic levels remains unchanged. Furthermore, it can be verified directly that the total excitaiton number operator

$$\hat{N} = a^\dagger a + \sum_{j=1}^{M} jA_j^\dagger A_j \tag{7}$$

commutes with the Hamiltonian. Thus, its eigenvalue N is a good quantum number in the interaction process described by H. For the cases of the two-level and three-level atom, we have

$$\hat{N}_2 = a^\dagger a + A_2^\dagger A_2 + 1 \tag{8a}$$

$$\hat{N}_3 = a^\dagger a + A_3^\dagger A_3 - A_1^\dagger A_1 + 2 \tag{8b}$$

which, apart from a constant, are the same as those introduced in Refs. 3 and 16.

Since $[H,\hat{N}] = 0$, the Hamiltonian H cannot connect eigenstates of $\hat{N}$ corresponding to different eigenvalues. Thus, the Hilbert space spanned by the energy eigenvectors can be divided into subspaces according to the eigenvalues of $\hat{N}$. All the eigenvectors in each subspace correspond to the same eigenvalue of $\hat{N}$. Therefore, the Hamiltonian can be diagonalized in every one of such subspaces.

Consider the state

$$|i,n\rangle = |i\rangle|n\rangle \tag{9}$$

in which there are n photons in the field and the atom is in its i-th level. The subspace with $N = M + n$ is spanned by the following set of vectors: $|M,n\rangle$, $|M-1,n+1\rangle, \ldots, |i,n+M-1\rangle, \ldots, |1,n+M-1\rangle$. Since the initial number of photons n is arbitrarily chosen, there are an infinite number of such subspaces. Subspaces corresponding to different N are orthogonal to one another.

An arbitrary state in the subspace specified by N can be represented by

$$|\phi_n\rangle = \sum_{i=1}^{M} C_{i,n+M-1}|i,n+M-i\rangle \quad , \tag{10}$$

where the coefficients $C_{i,n+M-i}$ are determined by the stationary Schrödinger equation,

$$\sum_{i'=1}^{M} (H_{ii}\delta_{ii'} + H_{ii'} - E\delta_{ii'})\, C_{i',n+M-i'} = 0 \quad . \tag{11}$$

The matrix elements in (11) are given by

$$H_{ii} = \langle i, n+M-i | H | i, n+M-i \rangle$$

$$= (n+M-1)\hbar\Omega + \hbar\omega_1 - \sum_{j=1}^{i-1} \Delta_j \qquad (12a)$$

$$H_{ii} = \langle i, n+M-i | H | i', n+M-i')$$

$$= \lambda_{i'} \sqrt{n+M-i'}\ \delta_{i,i'+1} + \lambda_{i'-1} \sqrt{n+M-i'+1}\ \delta_{i,i'-1} \quad , \quad i \neq i' \qquad (12b)$$

with the detuning parameters defined by

$$\Delta_i = \hbar\Omega - \hbar(\omega_{i+1} - \omega_i) \quad , \quad i = 1,2,3,\ldots,M-1 \quad . \qquad (13)$$

Equation (11) is a Hermitean matrix equation and can easily be solved. Therefore, we can write down the eigenvectors $|\phi_{n\sigma}\rangle$ of H with corresponding eigenvalues $E_{n\sigma}$, which satisfy the equation

$$H|\phi_{n\sigma}\rangle = E_{n\sigma}|\phi_{n\sigma}\rangle \quad , \qquad (14)$$

as

$$|\phi_{n\sigma}\rangle = \sum_{i=1}^{M} C^{\sigma}_{i,n+M-i} |i, n+M-i\rangle \quad , \qquad (15)$$

where the superscript σ labels the energy eigenstates in the subspace corresponding to N. There are M such states in each subspace. The orthonormality condition requires that

$$\sum_i C^{\sigma'}_{i,n+M-i} C^{\sigma}_{i,n+M-i} = \delta_{\sigma'\sigma} \quad . \tag{16}$$

The completeness relation is given by

$$\sum_{n=0}^{\infty} \sum_{\sigma=1}^{M} |\phi_{n\sigma}\rangle\langle\phi_{n\sigma}| = 1 \quad . \tag{17}$$

Hence, if the atom is initially in the level M, then the field-atom system can only be in subspaces specified by N = M, M+1, M+2,..., M+n,... at all times.

We can now define the density matrix in the Hilbert space of energy eigenvectors as

$$\rho_{n\sigma,n'\sigma'}(t) = \langle\phi_{n\sigma}|\rho(t)|\phi_{n'\sigma'}\rangle \quad , \tag{18}$$

which satisfies the equation of motion

$$\frac{\partial}{\partial t}\rho_{n\sigma,n'\sigma'} = -\frac{i}{\hbar}(E_{n\sigma}-E_{n'\sigma'})\rho_{n\sigma,n'\sigma'} \quad . \tag{19}$$

The solution of (18) takes the form

$$\rho_{n\sigma,n'\sigma'}(t) = \rho_{n\sigma,n'\sigma'}(0)\ \exp[-\frac{i}{\hbar}(E_{n\sigma}-E_{n'\sigma'})t] \quad , \tag{20}$$

where the initial density matrix is given by

$$\rho_{n\sigma,n'\sigma}(0) = \rho_{nn'}|n,M\rangle\langle M,n'|$$

$$= \rho_{nn'}(C^{-1})^{M}_{\sigma,n+M-\sigma}\,(C^{-1})^{M}_{\sigma',n'+M-\sigma'} \quad . \tag{21}$$

The last step is from the inverse transformation of (10), namely,

$$|n,M\rangle = \sum_{\sigma=1}^{M} (C^{-1})^{M}_{\sigma,n+M-\sigma}|\phi_{n\sigma}\rangle \quad . \tag{22}$$

If the initial density matrix is known, the mean values of all dynamical variables of the atom-field system can be calculated. The mean occupation probability of the j-th level is

$$P_j = tr(\rho A_j^{\dagger}A_j) = \sum_{n\sigma}\sum_{n'\sigma'} \rho_{n\sigma,n'\sigma'}\langle\phi_{n'\sigma'}|A_j^{\dagger}A_j|\phi_{n\sigma}\rangle$$

$$= \sum_{n,\sigma,\sigma'} \rho_{n\sigma,n\sigma'}(0)\; C^{\sigma}_{j,n+M-j}\; C^{\sigma'}_{j,n+M-j}\; \cos((E_{n\sigma}-E_{n\sigma'})t) \quad . \tag{23}$$

It is easily verified that

$$\sum_{j=1}^{M} P_j = \sum_{n,\sigma,\sigma'} \rho_{n\sigma,n\sigma'} \sum_{j} C^{\sigma}_{j,n+M-j}\; C^{\sigma'}_{j,n+M-j} = \sum_{n,\sigma} \rho_{n\sigma,n\sigma} = 1 \quad , \tag{24}$$

where we have made use of (16) and (17). The mean photon number is given by

$$\langle n\rangle = \mathrm{tr}\langle\rho a^{\dagger} a\rangle = \sum_{n\sigma}\sum_{n'\sigma'} \rho_{n\sigma,n'\sigma'} \langle\phi_{n'\sigma'}|a^{\dagger}a|\phi_{n\sigma}\rangle$$

$$= \sum_{n,j} (n+M-j) \sum_{\sigma\sigma'} \rho_{n\sigma,n'\sigma}(0)\, C^{\sigma}_{j,n+M-j}\, C^{\sigma'}_{j,n+M-j} \cos((E_{n\sigma}-E_{n\sigma'})t) \quad . \tag{25}$$

III. Results and Discussion

We now proceed to study (23) and (25) as functions of time. In our numerical calculations, $\hbar = 1$ is used throughout. We also take, for simplicity, $\lambda_1 = \lambda_2 = \ldots = \lambda_{m-1} = \lambda$, and $1/\lambda$ is taken to be the unit of time. The initial conditions are assumed such that the atom is in the uppermost level M and the field is in the coherent state

$$\rho_{nn} = \frac{\bar{n}^{n}}{n!} e^{-\bar{n}} \quad , \tag{26}$$

where $\bar{n}$ is the initial mean photon number in the field. Furthermore, we have also limited our calculations to the resonance interaction, even though our formalism is quite general and is valid for arbitrary detunings.

For definiteness, we calculate only the occupation probabilities P_M and P_1 for the highest and lowest levels, respectively, for M = 2,4,6 and 8. The results are plotted in Figs. 2 and 3. It is observed that the probabilities oscillate with the same number of peaks and valleys before collapse. When the initial mean photon number $\bar{n}$ is fixed, the oscillations slow down with increasing M. The amplitude of oscillation as well as the mean occupation probability both decrease with increasing level number M, as expected. Thus, the collapse time increases with increasing M. On the other hand, when the

level number M is fixed, the oscillating probability curves appear to be squeezed to the left as the mean initial photon number $\bar{n}$ increases. Thus, both the amplitude and frequency of the oscillating probability increase with increasing $\bar{n}$ for a given M.

Figure 4 depicts the time evolution of the mean photon number for $M = 2,4,6$ and 8 for the two cases with $\bar{n} = 5$ and 10. The shapes of the curves are seen to be essentially the same. The oscillation amplitude, the collapse time and the mean probability all increase as the number of atomic levels increases. For a given M, the oscillating curve is again squeezed to the left when $\bar{n}$ increases. Similar to the occupation probabilities described above, the level number M and the mean photon number $\bar{n}$ have opposite effects on the time dependence of the photon distribution.

In the experimental investigation of a single atom interacting with the one-mode cavity field, the measurement of ionization signals of the atom in an external electric field has been regarded as one of the most useful techniques.[12,17] It is therefore of interest to study the relation between the properties of the cavity field and atomic level occupation probabilities.

We now consider the slowly-varying complex field amplitude operators[14]

$$d_{1,2} = \frac{1}{2}(ae^{i\Omega t} \pm a^{\dagger}e^{-i\Omega t}) \tag{27}$$

and calculate the variance $\langle\Delta d_1\rangle^2$ as a function of time for $M = 2,4,6$ and 8. The results are shown in Fig. 5. As discussed in Ref. 14, the field is in the squeezed state whenever the variance becomes smaller than 1/4. Upon comparing Fig. 5 with Figs. 2, 3 and 4, we find that whenever the field enters the squeezed state from its initial coherent state, P_M is in the neighborhood of its minimum while P_1 and $\langle n\rangle$ are both in the neighborhood of their maxima.

The opposite is true when the field leaves the squeeze state and moves back to the coherent state, namely, P_M is around its maximum and P_1 and <n> are around their minima. Thus we always have $dP_M/dt > 0$, $dP_1/dt < 0$ and $d\langle n\rangle/dt < 0$ when the field is squeezed. These characteristics of the interacting atom-field system indicate the following. The process by which the field evolutes to and stays in the squeezed state for the first time corresponds to that by which the atom enters for the first time and stays in the absorption state, leaving the stimulated emission state. This implies that if the atom is initially in its ground state, the field enters into the squeezed state from the coherent state immediately when the interaction is switched on. The recent calculation of Shumovsky et al[18] has confirmed this. We believe that the conclusions we have reached in this paper should be useful in observing the squeezed state of the field.

In Figs. 6 and 7 we plot the long-time behavior of P_M and P_1 for $M = 2,4,6$ and 8, and $\bar{n} = 5$ and 10. The curves show the following interesting features. For a fixed $\bar{n}$, the regular envelope shape of the first revival gradually turns into irregular oscillations as M increases, and the first revival time t_r shows slight but steady increase with increasing M. The regular shape of the envelope is restored, however, when $\bar{n}$ increases for given M values. This means that only sufficiently strong fields can maintain the quantum collapse and revival phenomenon for mutlilevel atoms.

The time evolution of the mean photon number has similar properties to those of occupation probabilities as can be seen in Fig. 8. The first revival time of the mean photon number depends strongly upon the initial mean photon number $\bar{n}$ and the atomic level number M. An increase of either $\bar{n}$ or M can increase t_r. It is also noted from our numerical study that for small $\bar{n}$, irregular oscillations occur after the first collapse. As $\bar{n}$ increases, the

irregularity disappers and $\langle n \rangle$ becomes stable until the next revival. The numerical value of this stable $\langle n \rangle$ increases with increasing M. This is because the number of cascade photons is also increasing.

IV. Conclusion

We have developed a fully quantum mechanical theory to treat the interacting system of a cascading M-level atom and cavity fields of arbitrary detunings, and investigated numerically the collapse and revival phenomena of the atomic level occupation probabilities and mean photon number. Our results indicate that for a given $\bar{n}$, the first collapse time t_c increases with increasing M and that $\bar{n}$ and M have opposite influence on t_c. We have also found an interesting phenomenon. The field entering the squeezed state for the first time corresponds to the first absorption of the atom. This discovery should help the observation of the squeezed state in one-atom masers.

The first revival of occupation probabilities of multilevel atoms exhibits irregular oscillations as M increases, but the regular envelope can be restored by increasing the initial $\bar{n}$. The first revival time of the mean photon number increases quickly with increasing $\bar{n}$ and M. This is quite different from the occupation probabilities for which the revival time changes rather slowly, especially when M is large.

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Figure Captions

1. Schematic energy level diagram of the M-level atom.

2. Evolution of the highest level occupation probability P_M for $\bar{n} = 5$ (solid line) and $\bar{n} = 10$ (dot-dashed line). (a) $M = 2$, (b) $M = 4$, (c) $M = 6$, (d) $M = 8$.

3. Evolution of the lowest-level occupation probability P_1. Other notation is the same as in Fig. 2.

4. Evolution of the mean photon number $\bar{n}$. The scale on the left refers to the solid line ($\bar{n} = 5$), and the scale on the right refers to the dot-dashed line ($\bar{n} = 10$). (a) $M = 2$, (b) $M = 4$, (c) $M = 6$, (d) $M = 8$.

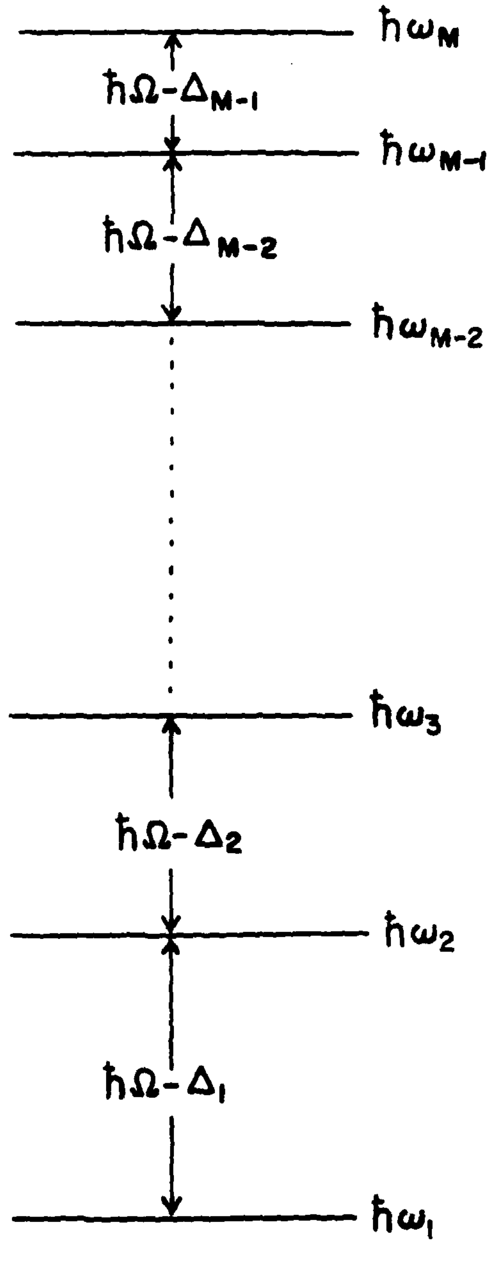
5. Evolution of the variance $(\Delta d_1)^2$. Other notation is the same as in Fig. 2.

6. Long-time behavior of P_M. (a) $\bar{n} = 5$ and (b) $\bar{n} = 10$.

7. Long-time behavior of P_1. (a) $\bar{n} = 5$ and (b) $\bar{n} = 10$.

8. Long-time behavior of the mean photon number. (a) $\bar{n} = 5$, (b) $\bar{n} = 10$.

Fig. 1



$\hbar\omega_M$
$\hbar\Omega - \Delta_{M-1}$
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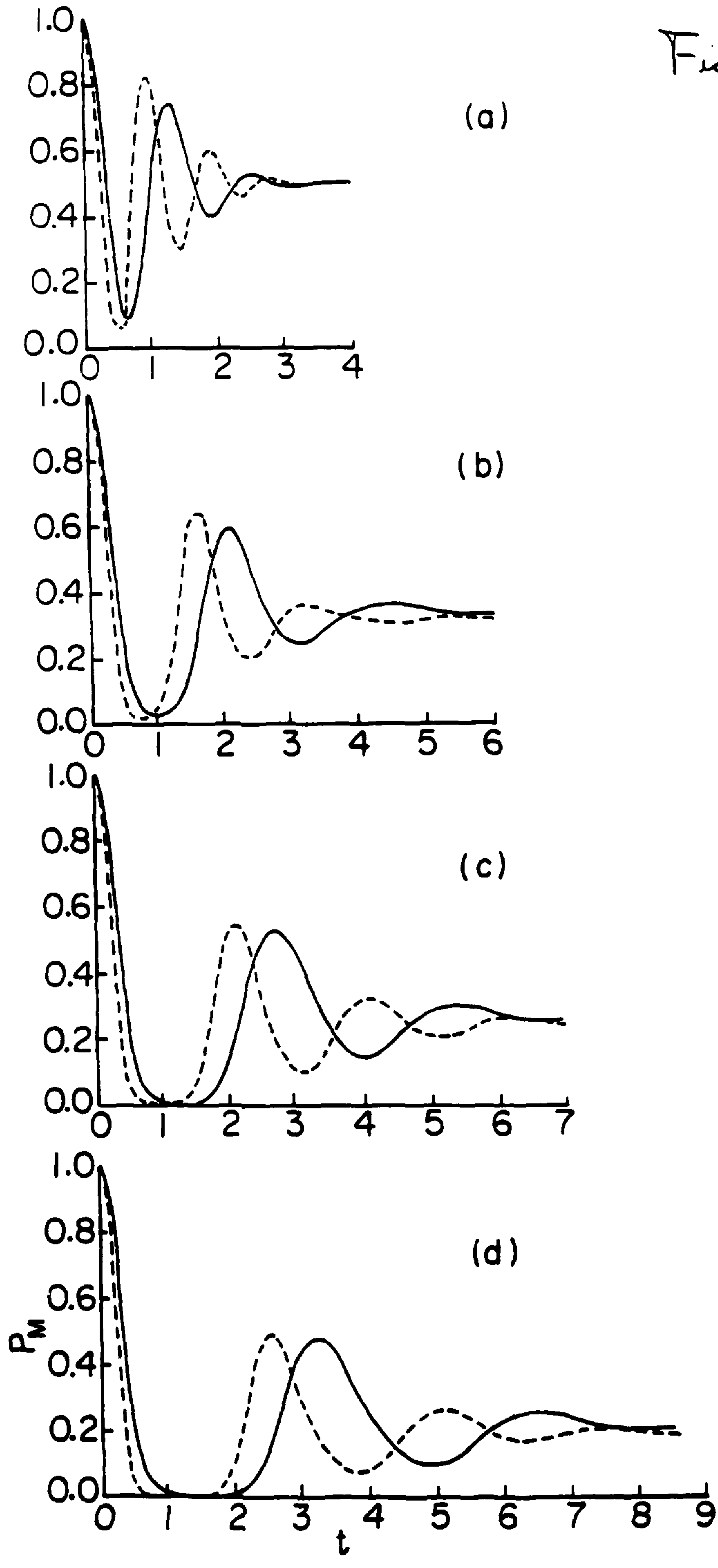

Fig. 2

Fig. 3

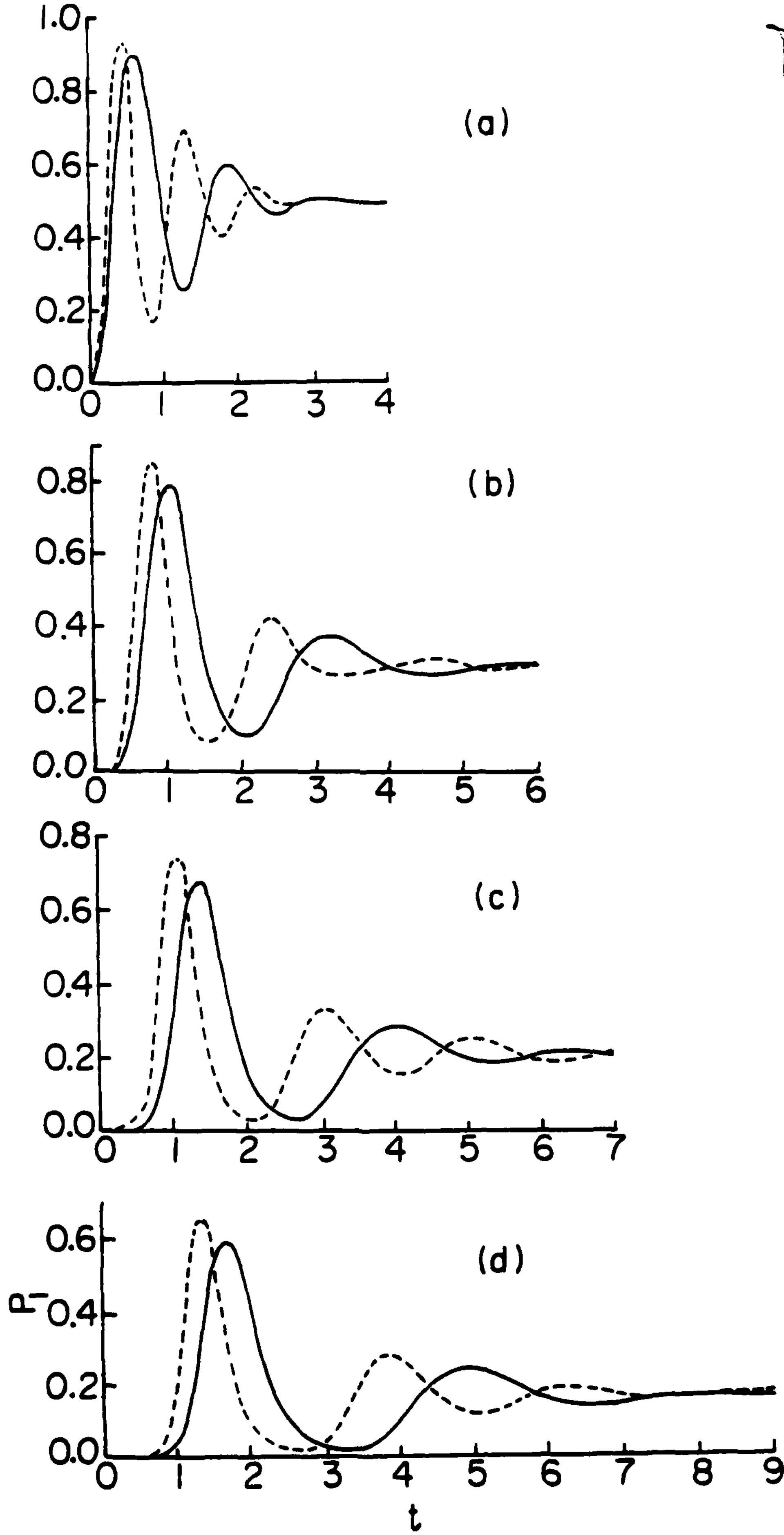

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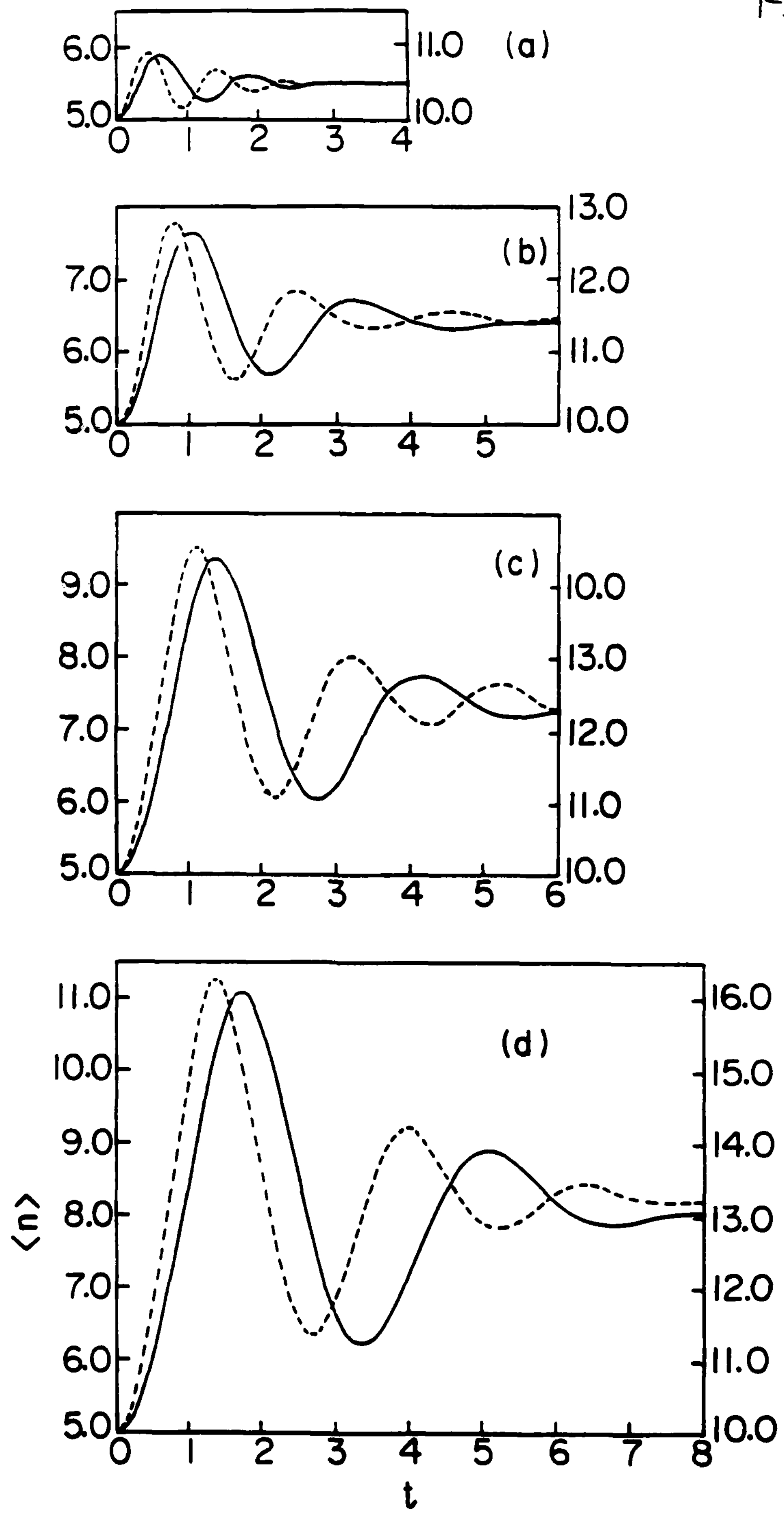
Fig. 4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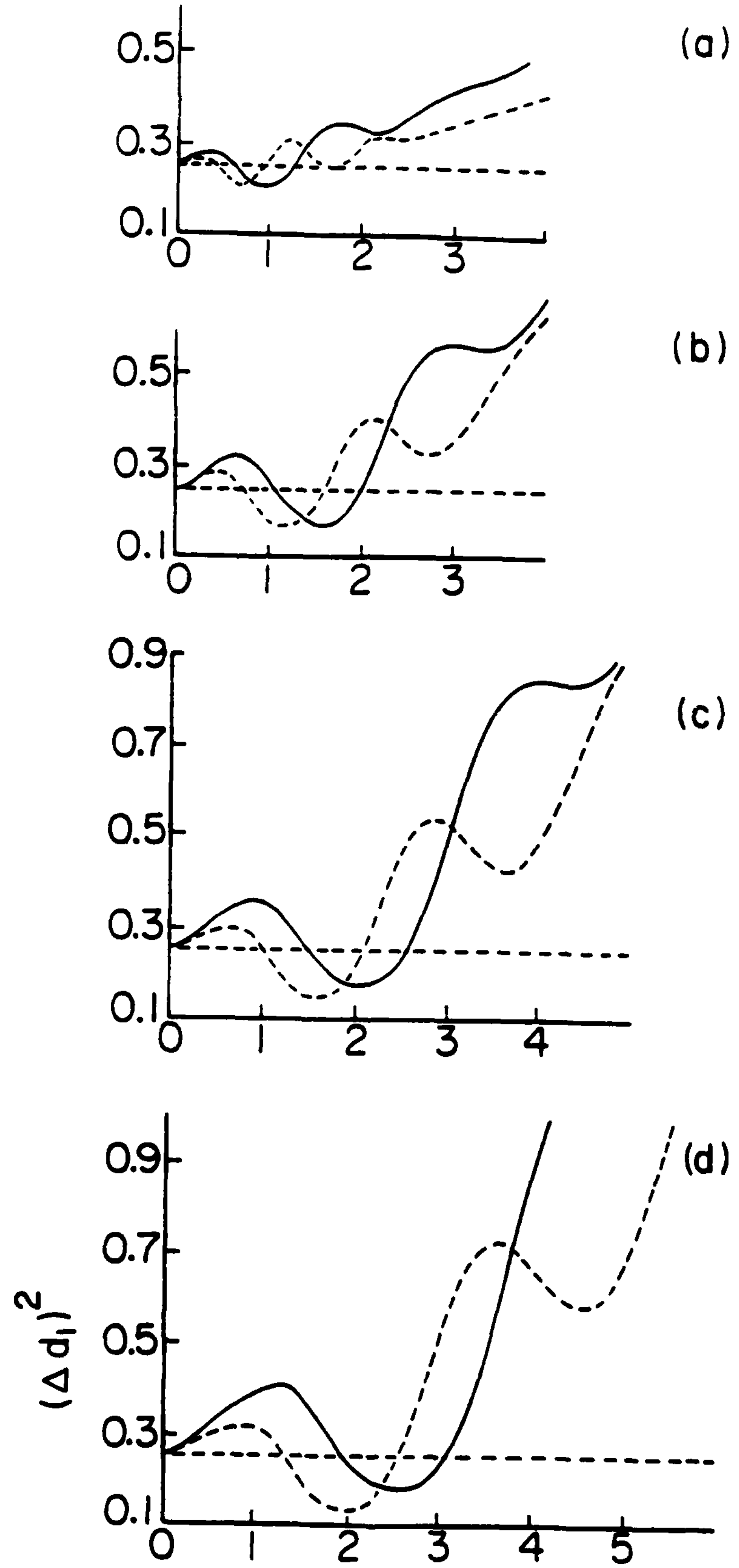
12.0
11.0
10.0
0 1 2 3 4 5 6
(d)
11.0
10.0
9.0
8.0
7.0
6.0
5.0
⟨n⟩
16.0
15.0
14.0
13.0
12.0
11.0
10.0
0 1 2 3 4 5 6 7 8
t

Fig. 5



(a)
0.5
0.3
0.1
0
1
2
3
(b)
0.5
0.3
0.1
0
1
2
3
(c)
0.9
0.7
0.5
0.3
0.1
0
1
2
3
4
(d)
0.9
0.7
0.5
0.3
0.1
0
1
2
3
4
5
$(\Delta d_1)^2$

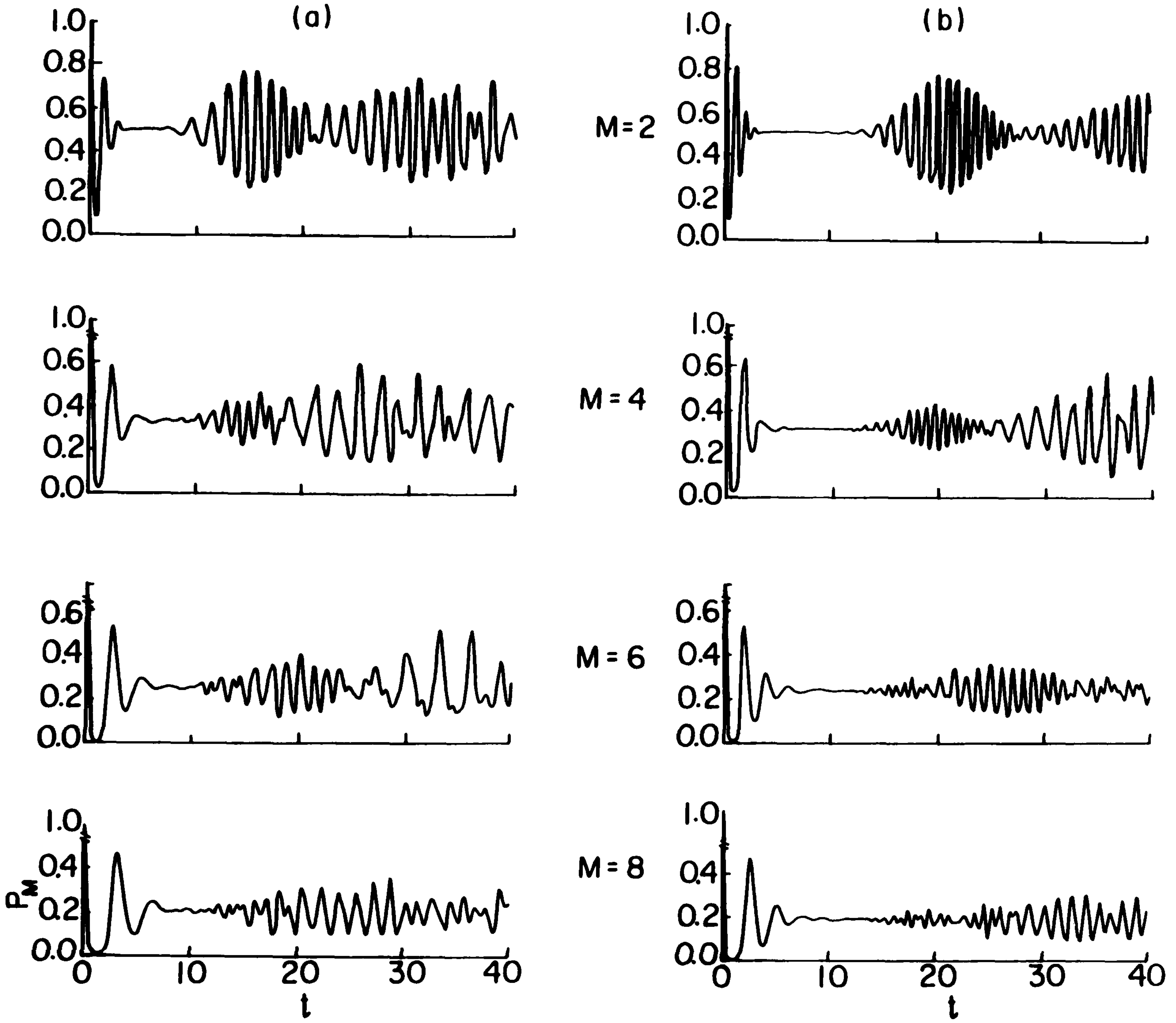


Fig. 6

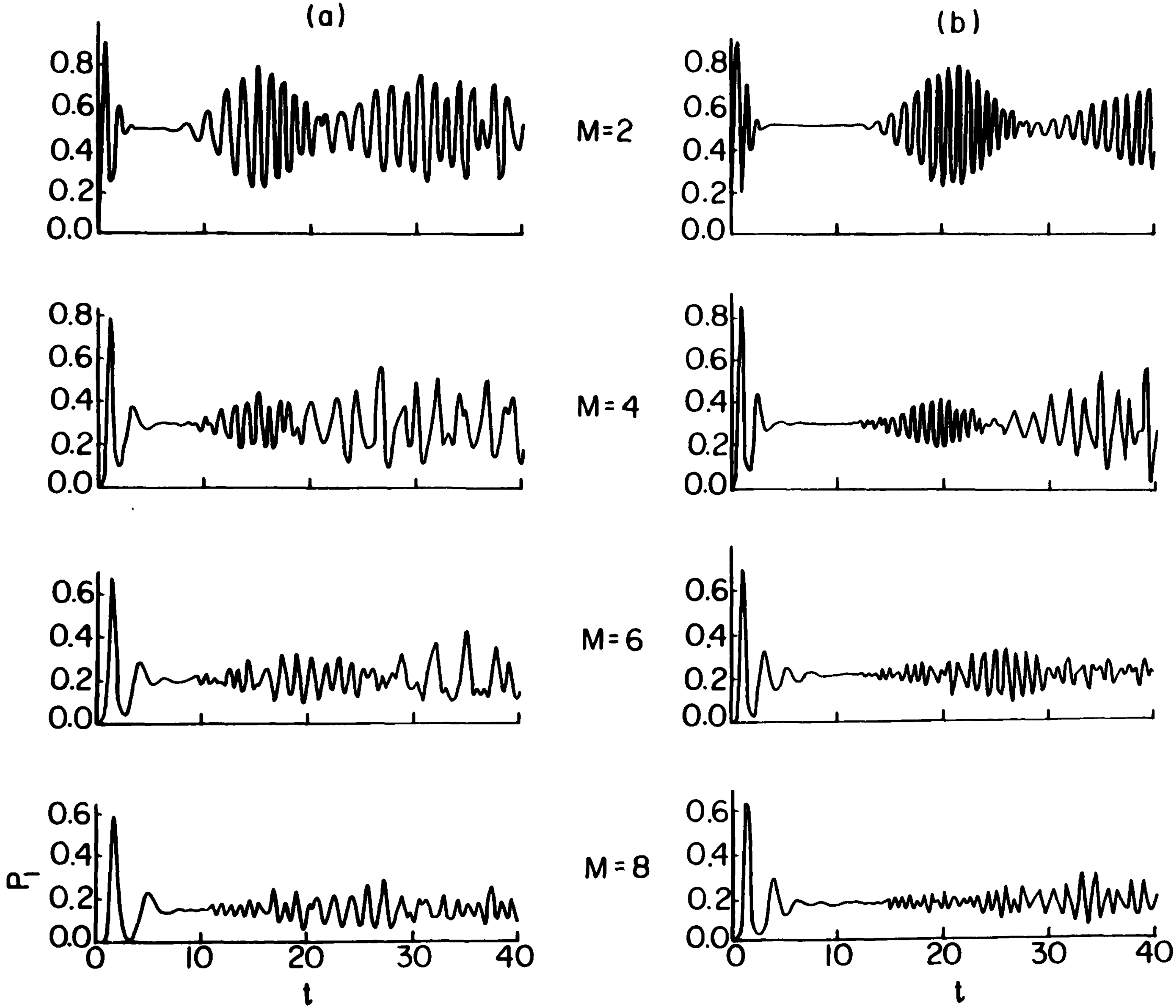


Fig. 7

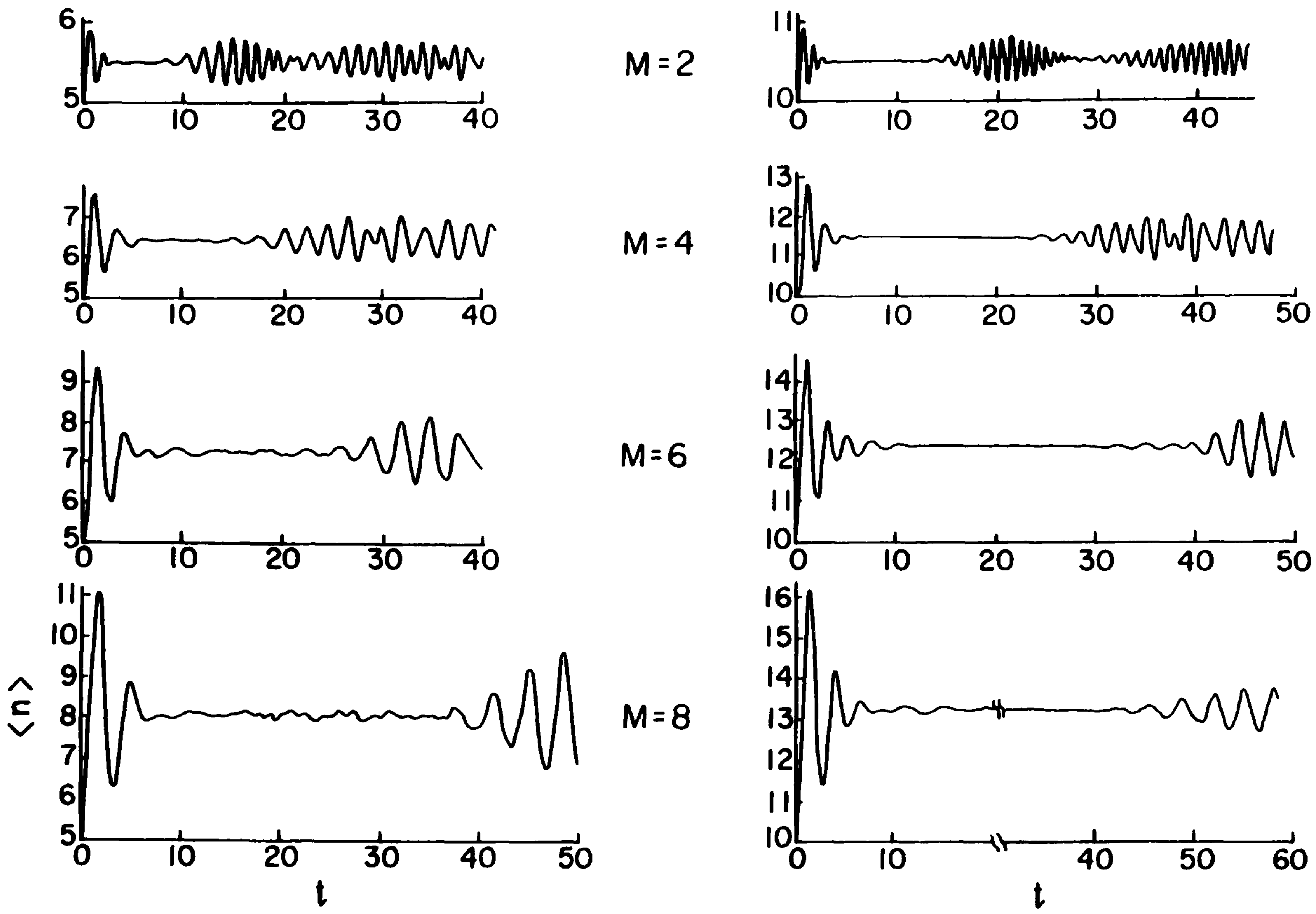


Fig. 8

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